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# RESEARCH AND DEVELOPMENT TECHNICAL REPORT

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# LIGHTNING PROTECTION SYSTEM DESIGN

*Applications for Tactical Communications Systems*

John M. Tobias
CECOM Safety Office

January 1993

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This report discusses design applications of lightning protection systems to military tactical/mobile communications equipment. New information from a recent test program discusses alternative, nonstandard materials for use that achieves levels of protection comparable to industry standards. Material specifications and assembly techniques are given for items validated by repeated exposure to 200,000-ampere simulated lightning current. The effects of lightning damage to system components is discussed. Design guidelines are presented addressing the specific problems encountered in tactical/mobile systems. Methods for predicting the probability of lightning strikes, and cost/risk analysis are considered to assist designers. Two case studies of existing systems are given to illustrate applications of the report recommendations. Data presented in the report provides tested advice to the communications system designer when industrial standards cannot be met because of overriding weight/mobility requirements.

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## Chapter 1 - Introduction

*History of Lightning Protection System Design in Tactical Systems*

Many older communication systems do not have lightning protection incorporated into their design. Designers thought that protection was not necessary in many cases because the antenna mast was relatively short (10 meters or less). The need for greater capability in communications systems forced designers to begin specifying taller masts and bigger dish antennas to meet the performance requirements. These taller and larger systems posed a greater probability of damage from lightning. Older masts constructed of metal frequently bonded a ground rod to the mast, effectively providing a ground path. Lack of design consideration for lightning protection is apparent on some systems as late as 1980. Again, requirements for lighter, more mobile systems drove designers to use nonconducting composites for their systems. These new materials made design revisions necessary to lightning protection systems.

The AB-621 series of masts did not originally incorporate lightning protection in its design. During testing of this antenna mast with an AN/TRC-138 Radio Terminal System at Ft. Huachuca in the summer of 1982, a lightning strike severely damaged this configuration (with the 100-foot AB-621). A better lightning protection system may have prevented this accident. We will review this incident later, to point out some design lessons.

In 1991, lightning protection was again an issue of the system designed to replace the AB-577/621 series of masts. While the design of the mast incorporated a well-designed lightning protection system, the materials used did not conform to the requirements of the National Electrical Code (NEC). Since this system uses a composite mast, it required a down conductor which is simply a wire to carry lightning current to ground. Engineers questioned the capability of this component to survive lightning currents imposed upon it. Designers pointed out that mobility requirements for this system precluded using the materials required by the NEC. No data existed on the use of alternative materials. We will also review this system in a case study to gain some design lessons.

*Review of Industry Standards for Lightning Protection*

The standards in the United States for lightning protection systems are the National Electrical Code (NEC), the National Fire Protection Association 78, *Lightning Protection Code* (NFPA 78), and Underwriters Laboratories 96A, *Standard for Installation Requirements for Lightning Protection Systems*, (UL 96A). An extract of these requirements is at tables 1 and 2.[1]

Please note that these tables are not comprehensive and that the respective codes have

[1] *NFPA 78*, p 78-8, National Fire Protection Association, Boston, 1989.

**Table 1** Class 1 materials - less than 75 feet.

| Component | Item | Copper | Aluminum |
|---|---|---|---|
| Solid Air Terminal | Min. Diameter | 9.5 mm | 12.7 mm |
| Tubular Air Terminal | Min. Diameter | 15.9 mm | 15.9 mm |
| | Wall Thickness | .8 mm | 1.6 mm |
| Main Conductor Cable | Min. Strand size | 17 AWG | 14 AWG |
| | Cross-section | 29 $mm^2$ | 50 $mm^2$ |
| Main Conductor Solid Strip | Thickness | 16 AWG | 14 AWG |
| | Width | 25.4 mm | 25.4 mm |

**Table 2** Class 2 materials - greater than 75 feet.

| Component | Item | Copper | Aluminum |
|---|---|---|---|
| Solid Air Terminal | Min. Diameter | 12.7 mm | 15.9 mm |
| Main Conductor Cable | Min. Strand size | 15 AWG | 13 AWG |
| | Cross-section | 58 $mm^2$ | 97 $mm^2$ |

additional requirements. The codes require modifications for special structures, etc. We merely point out the items of interest to us in our examination of lightning protection for tactical systems.

*Application of the Industry Standards to Tactical Systems*

Examining the industry standards, we quickly realize that they pose engineering constraints on communications systems. If you are designing a lightweight, mobile, 100-foot mast, the code requirements become a formidable obstacle. To comply with the code, you must specify a main conductor cable that is equivalent to 2/0 AWG wire. It weighs approximately 42 pounds for 100 feet and is difficult to wind on a spool. After one or two uses, it becomes quite kinked and unusable. In fact, if you search for a viable lightweight substitute to preserve the mobility requirements, you will find that compliance with the code is not possible. This was the problem that the AB-1373, the replacement for the AB-621 faced. It was an impediment to fielding the system. The problem is then simply stated:

> **What materials and design practices are suitable for application to tactical communications systems, when requirements preclude compliance to industry standards?**

This technical report provides the answer to the problem. The guidance presented is the result of a comprehensive test program that subjected several alternative materials to

simulated lightning currents, up to 215,000 amperes.

*How to Use this Report*

The technical information of this report is largely "modular." Each chapter and subsection is a module that addresses a specific lightning protection concern. If your main concern is application, proceed to chapter 3, Design Guidelines. The subsections of this chapter give detailed technical information on each component of the lightning protection system. If some information is not clear, use the index to find more detail. Chapter 1 reviews industry standards and provides information about lightning as far as it concerns the protection system. This is good reading for those who need to check if industry standards are applicable or those who need to understand lightning phenomena and its damage effects. If you are unsure about the need for lightning protection, proceed to chapter 2, Risk Analysis. This chapter details methods of estimating lightning strike probabilities, the risk associated with this hazard and estimating the cost of this damage extended over the system life. It can serve as a useful guide to justify additional cost incurred by addition of lightning protection. Chapter 4, Lightning Protection Applications, serves as a "sanity check" to review the results of your analysis against examples of previous lightning protection applications in systems. It can serve to highlight successes that you can apply and pitfalls to avoid.

If you are starting from scratch and your system needs a full treatment, that is, you are unsure of the need for lightning protection and its form, begin with chapter 2 to assess the lightning risk to your system. Based on your results, proceed to chapter 3 to design the protection you need. During this process chapter 1 can serve to provide reference material if needed.

*Lightning Characteristics*

A lightning strike is essentially a high amplitude direct-current pulse with a well-defined waveform. While there are several types of lightning, the type that concerns us in this report is **cloud to ground** lightning. Understanding of the waveform of cloud to ground lightning is useful to the designer in formulating a protection system, so we will discuss this phenomena. Precisely how lightning is generated and how it is propagated to earth does not impact design greatly, therefore it is not within the scope of this report. The lightning pulse is divided into four parts, components A to D. Figure 1 illustrates a lightning waveform. Component A is the high-current pulse. It is a direct current transient that has been recorded to reach up to 260,000 amperes and last for a duration of up to 200 microseconds. On the average, it will reach 20,000 amperes for a 50 microsecond duration. Strikes above 200,000 amperes are considered rare. Component B is a transition phase on the order of several thousand amperes. Component C is a continuing current of approximately 300-500 amperes that lasts up to .75 second. The last component, D, is a restrike surge that is typically half

that of component A in a given strike.[2] It has generally the same duration as component A. Typically 3 or 4 restrikes will occur in one lightning event but the maximum observed is 26 restrikes in **one** lightning event. Sources differ on the magnitude of 'D'; some state all restrikes are one-half the magnitude of the A component and some sources imply that the D component continually decreases by one-half (e.g., 1/2A, 1/4A, 1/8A, etc.). In this report, we use the first convention which is the worst of the two cases.

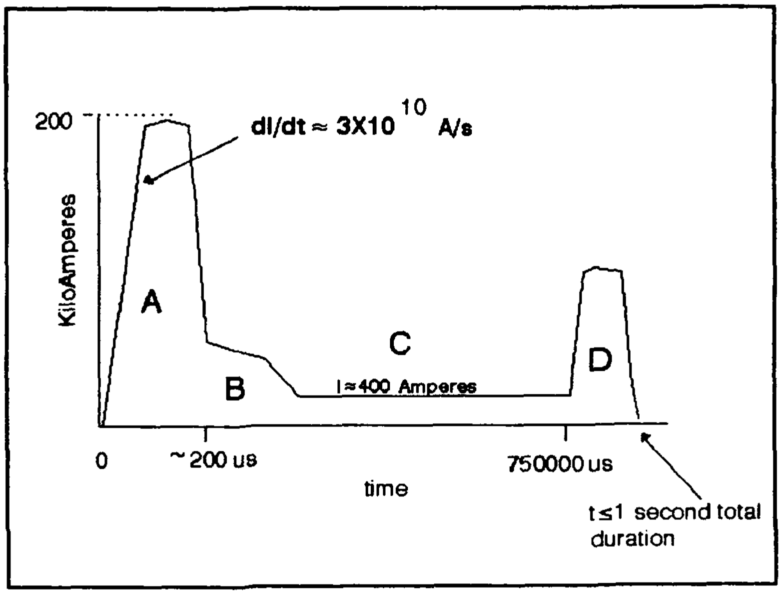


**Figure 1** Lightning waveform (not to scale).

Each component provides a different contribution in terms of damage phenomena. Components A and D contribute to the mechanical damage of the system. These components generate very strong magnetic forces (as predicted by the Biot-Savart Law) which can cause mechanical damage to systems. This force is capable of crushing tubular conductors and breaking wire conductors. During tests of various conductors, few could withstand exposure to currents above 170 kiloamperes. Figure 2 is an example of the mechanical damage that component A can cause. In this test, an aluminum braided conductor was exposed to a 150 kA peak simulated lightning event. Not only did the braid break, it essentially shattered, and split in two along its axis. These components of the lightning event do not contribute greatly to ohmic heating caused by the resistance of the wire. Since the duration of the A component is short, the total charge passed throughout the


**Figure 2** Aluminum braid after 150 kA.

[2] *Military Handbook 419, Volume 1, Grounding, Bonding and Shielding (Basic Theory)* p. 3-15, 1982.

conductor is comparatively small. The wire just doesn't have time to heat up.

Components B and C are primarily responsible for heating the conductor. The duration and magnitude of this component, approximately 1 second at 300 amperes, is enough to raise the temperature of the wire a few hundred degrees. For wires larger than #6 gauge, this current should not induce enough ohmic heating to damage the wire.

*Modes of Lightning Induced Damage*

Let's consider four modes of lightning damage in designing protection systems. They are blast, explosive vaporization, Biot-Savart induced mechanical damage, and ohmic heating. The latter effect is attributable to a different component of the lightning waveform, as discussed in the previous section. Blast is attributed to the nature of current propagation through the atmosphere, and is thought to be the overpressure generated by a high-temperature plasma from passage of the lightning stroke.[3] It causes the noise we call thunder. Explosive vaporization is the rapid heating of an item causing rapid expansion resulting in explosion.

Damage from blast is not recorded as a major damage effect. Some calculations have estimated the overpressure resulting from blast. Using a typical calculation, and approximating the energy release as $10^5$ joules,[4] we can plot the overpressure as a function of distance from the lightning stroke. This relationship is a simple inverse-square law, but we can see from figure 3 that significant overpressure can result close to the lightning stroke. Despite this explosive overpressure, few reports exist of damage caused by this effect. An accident reported in May of 1985 describes a detached retina, apparently caused by blast, in the passenger of a vehicle very near a lightning strike.[5] No data suggests that equipment is routinely damaged from this effect, and lightning protection systems do not seem affected by it.

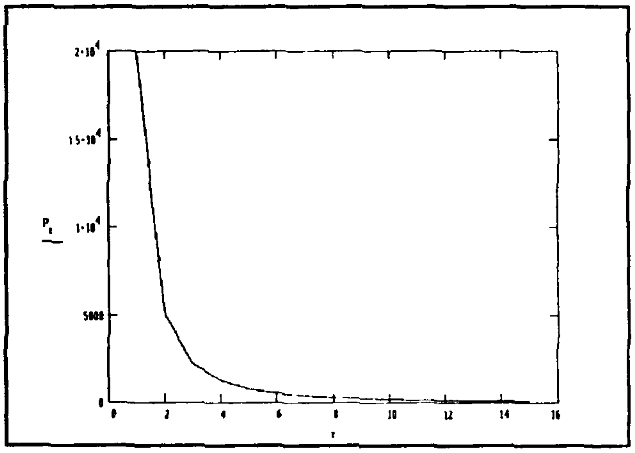

**Figure 3** Blast pressure (Pascal) vs. distance (meters).

Explosive vaporization occurs when the lightning strike causes water vapor trapped

[3] *Lightning*, p. 193, Uman, Martin A., Dover Publications, New York, 1969.

[4] *Lightning*, p.193-4, Uman, Martin A., Dover Publications, New York, 1969.

[5] U.S. Army Safety Center ASMIS Database.

in a material to rapidly vaporize and expand, causing an explosion. I witnessed explosive vaporization during a simulated lightning test. Insulation breakdown between components housed in a sealed fiberglass box caused flashover of a 150 kA stroke. This flashover caused rapid heating of some water trapped within the box which promptly caused it to violently explode. A classic example (literally) is a strike to the Temple of Aphaia at Aegina in Greece. Lightning strike to the temple caused a column to explode, scattering debris up to 15 meters away. Another famous case is mentioned by Golde in Venice where a tower over 100 meters high was wrecked nine times between the years 1388 and 1762. This destruction ceased after a lightning conductor was installed in 1766, according to Golde.[6] In our application, this damage effect is not of major concern. Mostly chimneys and similar porous structures are damaged by this effect.

Biot-Savart induced mechanical damage is the predominant damaging effect in lightning protection systems. This magnetic force can induce severe strain on any components that carry lightning current. My calculations indicate that pressures of 20 MPa and quite possibly higher pressures can exist within the down conductor of a lightning protection system[7] subject to a maximal lightning event. This is on the same order of magnitude as the yield stress of copper. Additionally, the steep waveform of the A component may cause non-uniform inward pressure throughout the length of the conductor resulting in *ductile* failure of the conductor. Test results suggest this, because the conductors exhibit diameter reduction at points of failure and elongation. Also, there is an apparent relationship between the tensile strength/yield stress and the survivability of the conductor when exposed to lightning currents. This effect is readily observable, especially in braided conductors because it causes the down conductor to "pinch." Constriction or apparent diameter reduction is observed throughout the length of the wire (in natural and simulated lightning), and might be the only indicator of a lightning strike.[8]

Ohmic heating induced by the B and C components is not the primary means of damage in lightning conductors, as was previously thought. A thermodynamic analysis can show that the heating is not enough to melt a copper wire of #6 gauge or more when exposed to the B and C component. A more likely effect is that an arc from the conductor to another path to earth will cause local heating resulting in damage to the conductor. I observed this in an antenna system (AB-1373) that was struck by lightning.[9] Local arcing from the down conductor to a steel guy wire caused the two to fuse together.

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[6] *Lightning Protection*, p. 114, R.H. Golde, Chemical Publishing Co., New York, 1973.

[7] *Lightning Ground Conductor Survivability - Engineering Notebook, Vol.1*, p. 26, John M. Tobias, unpublished.

[8] Trip Report - *Investigation of a Lightning Accident involving an AB-1373 DAMP Antenna Mast*, John M. Tobias, U.S.Army Communications-Electronics Command Safety Office, July 1992.

Another mode of heating damage is more subtle and deserves consideration. Diameter (cross-sectional area) reduction can occur when a conductor is exposed to lightning from ductile yield of the wire or from breakage of strands in a conductor. Since the relation for resistance is a function of the resistivity of the material and cross-sectional area of the wire, diameter reduction can cause a local point of high resistance. This point heats to a much greater temperature due to the higher resistance, melting the wire. Local heating from this cause occurred several times during testing resulting in conductor failure after the A component damaged a conductor by diameter reduction.

There are other damage effects from lightning, most notably electromagnetic pulse (EMP) and the electrical current. In terms of equipment protection we hope to divert the current by means of our protection system. Despite the diversion of the bulk of the current to the lightning protection system, there is no guarantee that the system will not experience a high-current transient. Installation of surge protection is essential for the prevention of damage. EMP and near-miss lightning strikes can also induce such a transient. Following other design standards for communications equipment will protect against such transients. Note that the current is especially hazardous to personnel. We will touch upon some hazards to personnel in a later section. Since design standards for surge protection and EMP are well documented elsewhere, we shall not consider it further, rather concentrating on the design of the lightning protection system.

## Chapter 2 - Risk Analysis

To determine the requirement for a lightning protection system we will analyze the cost vs. risk. This is accomplished in five steps:

1) Assignment of a system lightning mishap probability table.
2) Calculation of the probability of a lightning strike to the system.
3) Damage criticality assessment.
4) Risk level determination.
5) Cost vs. risk assessment.

In general, you must assess the risk from lightning if the system characteristics preclude compliance with the established industry standards. If you are unsure about the need for a lightning protection system, a cost-risk analysis is of benefit. The cost of a lightning protection system might not be justifiable for your application.

### *Definition and Tabulation of Risk Levels*

First, we must define risk levels to begin a meaningful risk analysis. This assignment is somewhat arbitrary, depending on the system characteristics. As a general guideline, we will use the risk criteria of MIL-STD-882B, *System Safety Requirements*. This method quantifies risk by assessing the probability and severity of a mishap. It ranks hazards into high, medium and low risk. Figure 4 details the MIL-STD-882 ranking system. We must now examine how to assign probability and severity levels.

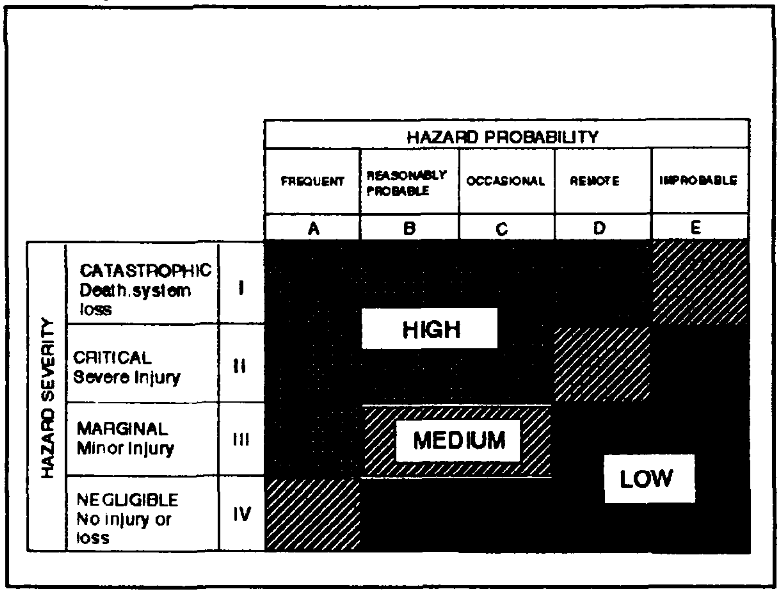


**Figure 4** Risk assessment table.

In table 3 are probability guidelines from the MIL-STD. These general guidelines are vague for our application and need further refinement. We must construct a probability table for the particular system. This assignment is somewhat arbitrary and it depends on what the engineer's classification of mishap frequency is. A separate table is constructed to accomplish the mishap probability assignment. An example is illustrated in table 4. The lowercase n denotes the number of systems concerned while the X denotes the number of mishaps from lightning. $X_1$ is the minimum number of mishaps considered frequent within the system life. Remembering the definition, it is continuously

**Table 3** Probability criteria.

| DESCRIPTION | LEVEL | INDIVIDUAL ITEM | INVENTORY/FLEET |
|---|---|---|---|
| FREQUENT | A | LIKELY TO OCCUR FREQUENTLY | CONTINUOUSLY EXPERIENCED |
| PROBABLE | B | WILL OCCUR SEVERAL TIMES IN LIFE OF ITEM | WILL OCCUR FREQUENTLY |
| OCCASIONAL | C | LIKELY TO OCCUR IN ITEM LIFE | WILL OCCUR SEVERAL TIMES |
| REMOTE | D | UNLIKELY BUT POSSIBLE TO OCCUR IN LIFE OF ITEM | UNLIKELY BUT CAN REASONABLY BE EXPECTED TO OCCUR |
| IMPROBABLE | E | SO UNLIKELY ASSUME OCCURRENCE WILL NOT BE EXPERIENCED | UNLIKELY TO OCCUR BUT POSSIBLE |

experienced within the entire fleet of systems. Similarly, $X_2$ is the minimum for probable occurrence, $X_3$ the minimum for occasional, etc. We will review the construction of this table in the actual case studies presented later in this report. Probability assignment may begin with the number of mishaps during the entire system life, the convention we use here, or may begin with number of mishaps per year, or number per day. The best one to use is the one that best enables you to realistically quantify the hazard. In our experience, we find that a top-down analysis can be the easiest.

A general guideline might be n>25% of the fleet suffering lightning mishaps over the life of the system is assigned "frequent," 15% to 25% of the system is assigned "probable," etc. Once this is decided upon, we can proceed to the next step which is quantification of the probability of lightning strikes to systems.

**Table 4** Probability assignment table.

| FREQUENCY | OCCURRENCES |
|---|---|
| CATEGORY | FLEET LIFE |
| A/FREQUENT | $X_1 \geq n$ |
| B/PROBABLE | $X_1 \geq n \geq X_2$ |
| C/OCCASIONAL | $X_2 \geq n \geq X_3$ |
| D/REMOTE | $X_3 \geq n \geq X_4$ |
| E/IMPROBABLE | $X_4 \geq n$ |

*Calculation of the Probability of Lightning Strike*

There are several methods documented to perform this calculation. We will limit ourselves to the methods that specifically quantify probability. There are several variables that factor into this probability calculation, such as system characteristics and construction and geographical location. We will consider each in turn.

The overriding consideration in this calculation is the geographical location. To consider this variable, we will define $D_T$, the number of thunderstorm days per year. Consistent with MIL-HDBK-419A, we define these as a 24 hour period, judged at local time, in which thunder is heard. We select this definition in order to utilize available meteorological data. Detailed maps with this data are available but we will generalize by geographical area. General values are presented in table 5. If more detail is desired, isokeraunic maps are found in MIL-HDBK-419. In many instances, a specific geographical location is not practicable since many systems are mobile and will operate worldwide. In this case, a worst-

case average value to use is approximately 60 thunderstorm-days per year. A more specific average can be calculated from the isokeranuic maps if desired.

Once this is known, determination of the fraction of the lightning discharges that strike ground is necessary. This fraction is dependent upon the geographical location as well. A formula in MIL-HDBK-419A, which relates this value to geographical latitude is written:

$$p=0.1(1+(\frac{l}{30})^2)$$

where $l$ is geographical latitude in degrees. For the operating areas listed we can approximate the fraction of strikes impacting ground as p=.33, corresponding to a latitude of approximately 45 degrees. Another way of interpreting this is that a third of all lightning will actually cause a ground strike.

**Table 5** Maximum average thunderstorm days per year by geographical location.

| Area | Maximum Average $D_T$ |
|---|---|
| CONUS | |
| Northeastern | 40 |
| Southeastern | 100 |
| Northwestern | 70 |
| Southwestern | 70 |
| Hawaii | 9 |
| Alaska | 6 |
| Europe | 20 |
| Korea | 10-15 |
| SW Asia | 5-10 |

With this knowledge, we can define a new term that considers all of the variables discussed. Let's call this the **flash density,** $F_D$, which is the number of lightning discharges that strike the ground in one year per square kilometer. This is given by:

$$F_D=0.007D_T^2p$$

Now we must relate system characteristics to strike probability. To consider the height of the system, we define a lightning attractive area. This calculation accounts for the evidence that objects that are higher than their surroundings attract lightning. There are two methods to calculate this area. The first method is advocated by MIL-HDBK-419 (Method 1), the other by R.H. Golde and other sources (Method 2).

Method 1: To calculate this area, we use the following expression:

$$A=\pi r^2$$

where:

$$r=80\sqrt{h}(e^{-.02h}-e^{-.05h})+400(1-e^{-.0001h^2})$$

and where h is the height in meters. The height in this calculation is really effective height, which means the height *difference* between the structure and its immediate surroundings.

(Consider objects within a radius of 2 times the actual height to be within immediate surroundings.) If the structure were an antenna mast deployed in the desert, the effective height is essentially equal to its actual height. In a forest it might be substantially reduced. Adjustment for deployment on elevated terrain is not necessary due to the nature of cloud to ground lightning. It is prudent to use the actual height because the area of deployment is often not known.[9] To simplify this, we can tabulate values for typical mast heights. These are presented in table 6.

**Table 6** Lightning attractive area for typical mast heights (Method 1).

| Mast Height (m) | Area(km$^2$) |
|---|---|
| 20 | .068 |
| 30 | .099 |
| 34 | .119 |

Method 2: This calculation is performed by simply considering the area as a function of the structures dimensions. Considering a structure of height h, length l, and width w, the lightning attractive area is then given by:

$$A = lw + 4h(l+w) + 4h^2\pi$$

In the limiting case, such as an antenna mast, this expression reduces to:

$$A = 4h^2\pi$$

which defines the attractive area about the mast.

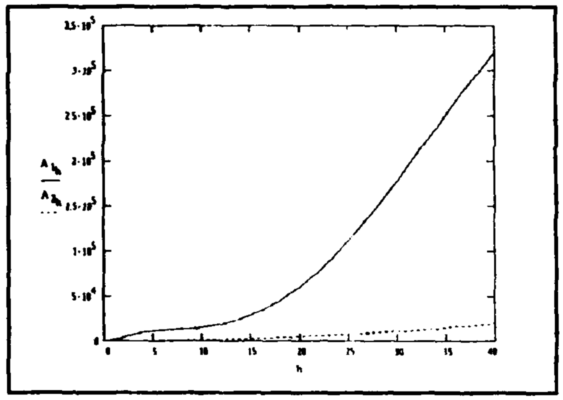

**Figure 5** Lightning attractive areas vs. height, Method 1 (solid line) and Method 2 (dotted line).

Method 1 is supposedly derived from curve-fitting available lightning statistics, while method 2 supposedly gives correct results within "an order of magnitude."[10] Method 1 gives a worst-case estimate while method 2 is obviously less conservative. In figure 5, which is a plot of the attractive areas in square meters vs. height in meters, this difference is obvious. Method 1 results in an attractive area about an order of magnitude greater at a 40 meter height. Determining which method to use requires some judgement. Use of the effective height in method 1 partially compensates for this. In general, it appears that use of method 1 is valid when a highly conservative estimate is required for

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[9] On the other hand, tactical systems are deployed to take advantage of natural concealment. Judgement requiring the engineer to assess the deployment mode of the system is needed to justify adjustment to the effective height.

[10] *Lightning Protection*, p. 41, R.H. Golde.

"point" systems, such as lone masts. For structures, method 2 appears the method of choice. **Note:** Each method of estimation is limited to structures of less than 300 meters in height. Lightning behaves differently near taller structures, invalidating these results.

Now we are prepared to determine the probability of a lightning strike on a given antenna system. Multiplying the flash density, $F_D$, by the lightning attractive area, A, we find the number of discharges per year that find our antenna mast. This assumes that the antenna is set up continuously during the year. Remember to select a value for $D_T$ that represents an average in all projected operating conditions, and that this might be weighted by which attractive area method is chosen. To properly account for the actual operational period, we adjust this by the ratio of operational days per year to days in the year. Let's call this value N, the fractional operating year.

$$N=\frac{\textit{operational days per year}}{365}$$

The formula to determine $H_{UY}$, defined as the number of strikes per operating year that find a given antenna, is:

$$H_{uy}=AF_DN$$

Think of $H_{UY}$ as hits per unit per operating year. Using method 1 for calculation of the attractive area and typical values from the tables for a 30 meter antenna mast and assuming operation 40 days per year with an average $D_T=20$ days per year, we can find this value to be approximately .01 strike per unit per year. Another way to look at this is that there exists about a 1% chance that an antenna operating under the specified conditions will experience a lightning strike within a year. To determine this number for a whole inventory of antenna masts, simply multiply this number times the number in the fleet times the operating lifespan in years. The formula is:

$$\textit{Total Strikes} = H_{uy}LI$$

where L is the lifetime in years and I is the number of antennas in the inventory. For our previous hypothetical example, let's use L= 10 years and I = 500 units. Performing the calculation yields 50 strikes per inventory life in our hypothetical antenna mast system.

To determine the rate of damage we must consider figure 6, which addresses the peak current versus incidence of strike. If the recommended #2 AWG copper wire is used as a down conductor, it is reasonably safe to say that the conductor will be in the 2% failure category. (NFPA 78 states that use of their recommendations precludes all known risk of melting due to lightning strike. To account for the possibility of maximum credible event, we reserve a 2% possibility of conductor failure.) That is, 2% of all strikes will cause damage to the system because of ground conductor failure. (Let's call this the material failure coefficient, C, for future reference.) To determine the incidence of damage, multiply

C by the number of strikes found in the previous paragraph. Performing the calculation on our hypothetical 30 meter antenna (50 strikes per inventory life x .02 = 1) we find that one strike in the inventory life will cause damage to the antenna or mast. As we mentioned previously, the problem is that the industry standards cannot be used for every system. In that case, relate the capability of a substitute conductor to a percentile level[11] in figure 6 and use that number instead. From a probabilistic viewpoint, we are 100% certain that one system will sustain damage within the operating lifetime from the example above. On the other hand, the probability of any given system sustaining damage within the hypothetical inventory lifetime is 1/500=.002 or about .2%. Note that this probability can be modified by several conditions. This result can be drastically modified if, for instance, field exercises are cancelled based on the forecasting of thunderstorms. In our estimation, this is not a good condition to attempt to factor into the calculation, as these systems may operate in combat conditions in any weather.

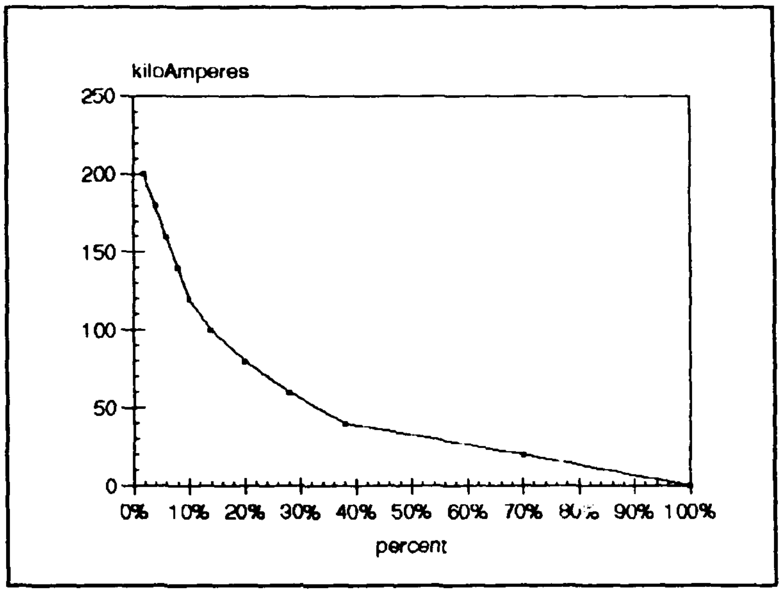


**Figure 6** Magnitude of lightning strike peak current (kiloamperes) vs. percent probability.

*Estimation of Lightning Damage Severity*

As with the construction of the mishap probability table, the damage criticality assignment is somewhat arbitrary. Consider the result if the lightning protection system were not present and judge what components would receive damage. Also consider the types of damage from mechanical effects, explosive vaporization and overcurrent if electronic components are present. Personnel injury is always considered, but, in general, there is no guarantee of personnel safety. The best place for personnel is in a grounded permanent structure, enclosed vehicle or a grounded communications shelter with the signal and power inputs disconnected. Several other effects of the lightning current (such as flashover and step potential) are very hazardous to personnel despite the installation of the most effective lightning protection system. In design, locate personnel as far as possible from any component of the lightning protection system.

[11] Data compiled from *Lightning and Lightning Protection*, Hart, W., and Malone, E., Don White Consultants, Gainsville, Virginia., 1979.

We can use a few general guidelines to construct an equipment damage severity table. The first is the accident classification guidelines from Army Regulation 385-4. Using this guidance, total system loss or damage in excess of $200,000 is considered in the Catastrophic category. From $50,000 to $200,000 is critical, $10,000 to $50,000 is marginal, and less is negligible. Many antenna systems are not nearly that expensive; in such cases a percentage of unit cost might be used. An example might be: 75% cost to repair is catastrophic, 50% is critical, 25% marginal and 5% or less is negligible. If you desire a more mission-capability oriented assessment, you may wish to link the damage criticality to repair time. In this case, system loss is catastrophic, depot repair is critical, direct support repair is marginal, and user/operator repair is considered negligible. Time to repair the damage might also be considered, regardless of the level of maintenance required. Again, it requires judgement on the part of the designer. Experience with communications systems (such as antenna masts) implies that only very rarely will lightning cause catastrophic damage. Usually the damage will be marginal to critical at most.

*Risk Assessment and Cost Analysis*

With assignment of damage probability and damage severity, classification of the risk is simple. Using the chart in figure 4, cross-referencing both parameters will yield a "high," "medium" or "low" risk assignment. Of course, if the risk is medium to high, redesign to improve the lightning protection is necessary.

To analyze the cost benefit of the lightning protection system, we can consider the previous definitions. Multiply the cost per incident from the damage severity table discussed above times the predicted number of lightning accidents in the system life. This value is the total expected cost of lightning accidents. If this calculation is performed on the system without lightning protection (e.g., set the material failure coefficient $C=1$) the difference between the second and first figures is the cost difference between a protected and unprotected condition. Comparison of this cost to the cost of the materials to install a lightning protection system can provide effective guidance on whether to install or improve lightning protection in the equipment under study.

With the data provided by the risk classification and a cost analysis we have determined the method by which the engineer can determine the need for lightning protection and defend the cost of installation. Usually, the relative cheapness of the lightning protection system (an effective system can be as inexpensive as $100, materials only) will override arguments against its installation, particularly in expensive, high-density, or long-lived systems.

## Chapter 3 - Design Guidelines

The lightning protection system for most communications system applications consists of only three assemblies: the air terminal, down conductor, and grounding subsystem. In this section we explore the design criteria with emphasis on the special problems of tactical systems. These design guidelines are based on research and the results of a test program conducted by the CECOM Safety Office. Recommended lightning protection solutions in this report are validated by test.

### *Air Terminal Design Considerations*

Use of an air terminal, also called the lightning rod, was known in the late 1700's. Very little has changed since the introduction of this device. Several variations of air terminal have been proposed and tried over the past several hundred years. These variations include a spiked ball arrangement and even air terminals with radioactive tips. Available data does not support any improvement in lightning protection from these variant configurations.[12]

In designing the system, consider the "zone of protection" afforded by the air terminal. Several studies beginning in the late 1800's and as late as the 1960's attempt to quantify the protective zone assigned to an air terminal. According to the NFPA 78, the definition of zone of protection is "...that space adjacent to a lightning protection system that is substantially immune to direct lightning flashes."[13] Several geometric interpretations exist for this protective zone. These concepts are readily reduced to practical design guidelines which we present next.

The protective zone interpretation we will use is a cone that extends from the tip of the air terminal to the ground. Different levels of protection are assigned to various conical regions, each a function of the apex angle.

Table 7 gives the statistics for each zone. The theory is that lightning of greater amplitude has a greater striking distance. Therefore the probability of lightning striking within the protective zone is inversely proportional to the apex angle. In figure 7, objects within region A have a higher probability of a lightning hit than items in region B. Table 7 details the

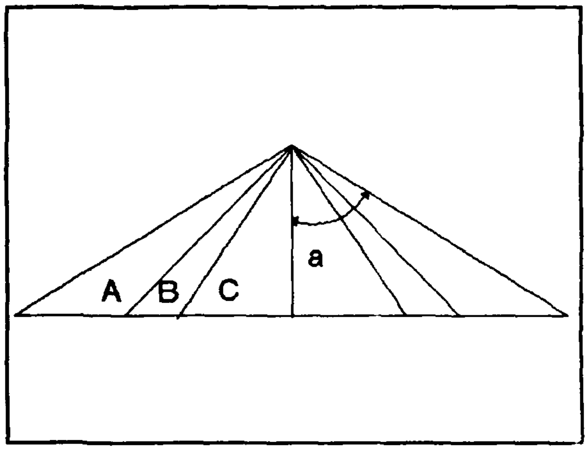

**Figure 7** Protective zones.

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[12] *Lightning Protection*, p.41, R.H. Golde.

[13] NFPA 78, p. 78-7, 1989 Edition.

ground coverage radius as a ratio of height, and the apex angle for each region is given. Various codes and practices[14] cite region A acceptable for ordinary structures, region B for important cases and region C for critical structures. In our design practice we recommend that the designer provide at least a 45 degree cone of protection for the system. A smaller apex angle is desirable. Figure 8 illustrates a good example of lightning protection installation. The extremities of the dish antenna in this case are enclosed by approximately a 38 degree apex angle. We wish to keep the air terminal as short as possible to prevent it from bending in high wind or breaking from the mechanical effects of a lightning strike, but still provide an adequate cone of protection. This is most difficult and most critical at the top of the mast. If any component of this antenna assembly were outside a reasonable cone of protection it would at least partially nullify the function of the lightning protection system. It is important to contain the components of the system within a reasonable cone of protection, while making the air terminal as short and sturdy as possible.[15]

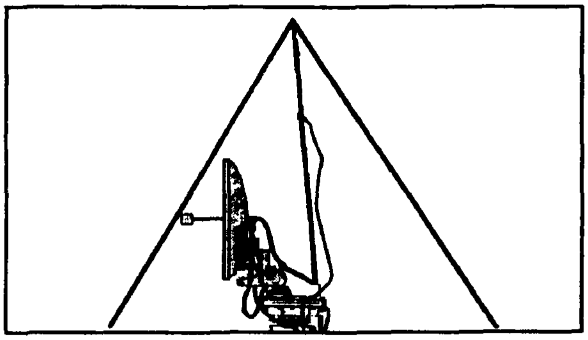

**Figure 8** Example of protective zone containing dish antenna.

**Table 7** Protective zone statistics.

| Zone | D/H | a |
|---|---|---|
| A | 2 | 63 |
| B | 1 | 45 |
| C | .58 | 30 |

If an array of several antennas is used, more than one air terminal might be necessary. In this case a lightning protection system might consist of two or more air terminals and a "middling wire." (This is the original term coined by Benjamin Franklin in his lightning studies.) The height of the middling wire and the air terminals is also sufficient to provide a 45 degree cone of protection to the antenna assembly. The middling wire is installed at a sufficient height above the protected equipment to prevent flashover to the protected equipment. A method of calculating clearance derived from

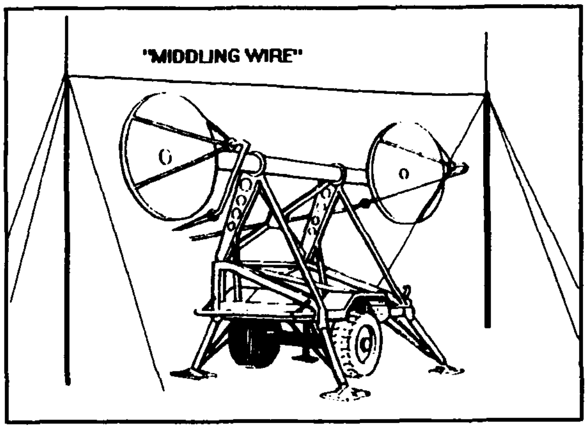


**Figure 9** Middling wire.

[14] MIL-HDBK-419A cites NFPA 78, NEC and British Code in this regard.

[15] Many standards require a brace for air terminals above 2 feet in length. This is to provide additional mechanical strength from blast and elements.

the breakdown potential of air is given by Golde.[16] Consider the potential at the point of the lightning strike to the system. This can be calculated by the expression:

$$v = I_{max}R + L\frac{dI_{max}}{dt}$$

Where: $I_{max}$=200 kA
R=system resistance
L=system inductance

To find inductance in this particular system, the following relation is used:

$$L = 2\times10^{-7} l \times \ln(\frac{2h}{r})$$

Where: l=middling wire length (meters)
h= average height above ground (meters)
r= wire radius in centimeters

The result L, is in units of henries. When considering R, the value used strictly should be the sum resistance of the whole system including the resistance to ground. The resistance to ground should be much greater than the sum of system resistance, therefore, R=resistance to ground. If this is not known, 50 ohms is a fair estimate. Once the value for L is calculated, dI/dt is known as $5\times10^{10}$ A/s, and the potential, v, is easily found. Using Golde's value for the breakdown potential of air per unit distance (900 kV/m), the minimal separation distance is easily found:

$$\frac{v}{v_{air\ breakdown}} = \frac{v}{900\frac{kV}{m}} = D\ (meters)$$

Only copper and aluminum are specified by the industry codes for the material of the air terminal. It appears that the intent of this is to prevent corrosion and rusting from reducing the effectiveness of the lightning protective system. A tactical system will not remain stationary for extended periods, so this is not a concern. At least one antenna system fielded uses a stainless steel air terminal. If a steel terminal is desired, include instructions in the Preventive Maintenance Checks and Services (PMCS) to allow for inspection and cleaning of the air terminal. However, we highly recommend the use of a copper air terminal. Steel has approximately an order of magnitude greater resistance than copper (per unit length) and it creates a higher resistance bond than copper. Minimization of resistance in the lightning protective system is of paramount importance. A higher resistance will cause current to seek alternative paths, possibly causing damage to equipment. As demonstrated above, resistance is proportional to flashover distance. Industrial codes imply that the middling wire material is identical to that for the down conductor in the class I/II material requirements. If this is impractical, test data indicate that 6.35 mm (1/4 inch) diameter steel cable will work to a high level of effectiveness (1/4 inch steel suffers no degradation after several exposures to

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[16] *Lightning Protection*, p. 100, Golde, R.H.

180 kiloamperes). Again, we recommend copper for lower resistance, but it may be impractical for application in the middling wire.

*Down Conductor*

The CECOM Safety Office conducted extensive testing and research to determine adequate down conductor materials for tactical systems. As portrayed in chapter 1, this component of the lightning protection system is most often the limiting factor because of weight, flexibility, and durability requirements.

In the test program conducted, materials considered were drawn from existing systems; proposed systems and new materials were tested for comparison. As a result, several alternatives exist for the equipment designer. Ultimately, if weight or size are critical constraints, the designer may need to consider tradeoffs between size/weight and protection. The risk assessment and cost analysis methods in chapter 2 provide the designer with an adequate tool to consider the alternatives. In these analyses, the major variable of interest is the material failure coefficient, C. Let's consider typical down conductor materials for this property.

The material failure coefficient, C, is defined as a decimal representation of the percentile region of the component A current generated in lightning strikes that a particular material is expected to fail. Simply put if $C=.02$, we expect the conductor to fail when exposed to a lightning strike in the upper 2 percentile. When determining C, we considered that 2-4 restrikes (component D) typically occur in natural lightning. Therefore the conductor materials were proofed at four strikes at the maximal rated component A current. Table 8 provides ratings for down conductor materials. Relationships between the yield stress (and hence tensile strength), cross-sectional area, and survivability exist. The items in the table were tested and proven out for the current rating assigned to the particular material failure coefficient. If the NFPA 78/NEC recommendations are not practical for your system, we recommend that you consider the materials in table 8. The lowest possible value is desirable for C. From the results of testing, #3 copper braid as specified in the table performed the best. Steel cable, 1/4 inch, performed nearly as well, but we consider it an alternative because of its higher resistance.[17]

When routing the down conductor in the system, consider the potential for flashover. As illustrated in the middling wire example, there exists a minimum clearance between the down conductor and other components. In the family of systems we are especially interested in,

[17] Several foreign codes allow for steel down conductors in their lightning protection systems. Despite the fact that U.S. code does not allow for steel down conductors, our testing suggests that steel performs possibly better than copper and certainly better than aluminum.

**Table 8** Down conductor material statistics.

| WIRE | SPECIFICATION | $\sigma$ $mm^2$ | C | Mass/length (kg/m) | Durability/ Flexibility |
|---|---|---|---|---|---|
| #6 AWG COPPER | SOLID, .4115 cm dia. | 13.30 | .08 | .12 | Good/ Poor |
| #6 AWG COPPER | 7 STRAND , .1549 cm dia/strand .4674 tot | 13.19 | .15 | .10 | Good/ Poor |
| #6 BRAID COPPER | FLAT, 2.54 cm X .114 cm, 32 AWG strands (.0201 cm dia.), 396 strands. | 12.57 | .15 | .11 | Good/ Good |
| #6 WIRE COPPER STRAND | CIRCULAR, 27 AWG strands, 133 strands. | 12.57 | .15 | .12 | Moderate/ Moderate |
| #3 BRAID COPPER | FLAT, 3.81 x .152 cm, 30 AWG strands (.0255 cm dia.), 528 strands | 26.97 | .02 | .25 | Good/ Good |
| #4 WIRE COPPER | CIRCULAR, 25 AWG strands, 133 strands | 21.63 | .08 | .20 | Good/ Moderate |
| Steel Cable | CIRCULAR,1/4 in. dia. "Steel aircraft cable" | ~20 | .02 | .16 | Good/ Moderate |

the problem gets complicated rapidly because of guy wires, signal inputs and waveguides. First we consider methods of calculating the suggested clearance for the down conductor.

We shall use a similar approach as before to calculate the minimum clearance. Also consider that different types of conductor (e.g., braided, etc.) have different properties that affect the inductance. The formulae from MIL-HDBK-419 for the inductance of flat conductor is:

$$L=.002l(\ln(\frac{2l}{b+c})+.5+.224(\frac{b+c}{l})\ \mu H$$

and for circular conductors:

$$L=.002l(\ln(\frac{4l}{d})-.75)\ \mu H$$

Note that all dimensions are centimeters, where l=length of the conductor, b=width, c=thickness and d=diameter of circular conductors. The result is in units of microhenries.

By repeating the calculation in the previous section:

$$\frac{v}{v_{air\ breakdown}} = \frac{v}{900\dfrac{kV}{m}} = D\ (meters)$$

the minimum clearance is determined. Typical results are in the 2-3 meter range, which is often too large to achieve in some systems. Consider an antenna mast with lightning protection. Such a system has the antenna, air terminal, down conductor, signal cable or waveguide and guy wires in close proximity at the apex of the mast. All are within .5 meter of each other. Examining the signal cable first, we can determine the breakdown value of its insulation and add it to the potential, v, in the above equation. With insulation considered, the minimum clearance should get much smaller and no longer be critical. If the guy wires are nonconductive, this need not be considered. If they are of steel, they may carry a portion of the lightning strike to ground. This is suggested by a limited amount of data, but is not necessarily hazardous. If the guy wires are at least 1/8 inch steel the probability of lightning current causing damage is low. A waveguide is a good lightning conductor. Few means are practical to protect it, but available data suggest that it might not be damaged by flashover. Since other standards require bonding of waveguides to the grounding system, flashover to the waveguide should not be hazardous. As for the antenna itself, the flashover probably will not damage it, but current may travel in the signal cable. Since surge protection is required on signal inputs, this should not be hazardous. Furthermore, no accidents are recorded where antenna assemblies have been significantly damaged in a lightning strike to a protected system under similar conditions. From all the data that we have, effects from down conductor flashover are minimal to nonexistent. If additional protection is deemed necessary, consider routing the down conductor through an insulator with a high breakdown potential, such as polyvinyl chloride pipe. This may be a good precaution if the down conductor is within the minimum breakdown clearance distance of critical or especially delicate components.

Another consideration is the use of structural components as the down conductor. Various codes permit this practice. Electrical continuity is the prime requirement. The structure should at least meet the class I/II material requirements as well. That is, the conducting cross-section should equal the required size. The other factor on material selection is the magnetic force induced by the A component that can cause collapse of tubular components. Rough calculations of this force on a tube 25 meters long, .05 meter in diameter with a wall thickness of .005 meter, subject to a 200 kA lightning strike, yields an inward pressure of approximately 10 kPa. (The dimensions approximate the size of a typical antenna mast.) By calculating the permissible "hoop stresses" in an equivalent SAE 6061 aluminum tube (a likely material) we find that it is orders of magnitude greater than the induced stresses. In general, a permissible hoop stress of approximately 1 MPa should prove adequate for these structural components. Despite the convenience of using system components as part of the lightning protection system, there are significant disadvantages. When we discuss bonding

requirements, we will see that maintenance of electrical continuity in this type of system might prove difficult.

Mechanical damage to down conductors can adversely affect their performance. No bend in the lightning protection should exceed 90 degrees with a 6-inch bend radius. Keep the conductor as straight as possible. (Loops and such can also create an inductive loop, raising the potential for flashover and damage to the system. An interesting example will be presented in Case Study 2.) Test data explicitly show that kinks in the conductor will be violently torn apart by the lightning current, causing protective system failure. Consider this in the design in order to prevent procedures or installations that subject the down conductor to excessive wear and tear. Include inspection of the down conductor in PMCS. If the down conductor is torn, frayed, excessively kinked or twisted, replace it as soon as possible.

*Connectors*

Connections in the lightning protection system must have low resistance and mechanical strength. The junctions between the air terminal, down conductor and ground rod are critical points for system damage. Three types of connectors were tested by the CECOM Safety Office as likely candidates for use in lightning protection systems. Let's examine the necessary material properties of the connectors and examine their achievement in application.

Mechanical strength is a critical characteristic. The connector must hold and maintain a contact pressure suitable to prevent the conductor from loosening from magnetic forces, but must not cause the conductor to pinch or crease. A pinch or crease in the conductor causes a local weak point in terms of electromagnetically induced damage and a point of increased local resistance causing excessive ohmic heating. Either way, it can result in system failure. As mentioned, three tested selections are available that are suitable for lightning protection applications.

The first connection we consider is a simple lug and bolt arrangement. It is commonly found on standard ground rods. Testing indicates that a closed-end lug is most effective. Installation of the lug on the down conductor was done by fitting a copper lug to the conductor (#3 copper braid), lightly crimping it in place and brazing it to the conductor. The rod used was a standard steel MX-148/G ground rod illustrated in figure 10. In this method, exercise care not to over-crimp the lug. A closed lug is essential to prevent it from tearing off of the bolt. Tests demonstrate that the bolt can loosen significantly when subject to the lightning current. An open lug might not survive more than one lightning strike, while the closed lug survives four or better. In specifying installation procedures, it is important to specify tightening the bolt with a tool such as a pliers or wrench. Significant loosening was observed in hand-tightened bolts.

The next type of connector tested is a fitting found on the AB-1373 mast. It is useful in cases where requirements dictate a temporary bond between a ground rod and the down conductor. Figure 11 provides a side view. A wingnut provides compression to the

ground rod, which in turn holds the cable in place. The connector is constructed of brass. In the configuration tested, the down conductor was inserted between the rod and the back of the connector. This provided the maximum surface area for the bond, and reduced wear and tear on the conductor. When subject to lightning currents, it also became somewhat loose. Consider tightening the bolt with a hand tool as in the previous case and leaving at least 6 inches of excess down conductor threaded through the connector. Otherwise, this conductor tested well repetitively at the 200 kA (2%) level.


**Figure 10** Lug and bolt connection.

A "U"-bolt arrangement was the third type of connection considered, illustrated in figure 12. The down conductor was again placed under the rod to maximize the bond area and secured in place by the U-bolt. The U-bolt was tightened by a wrench. This arrangement tested with no observable degradation or loosening from repetitive strikes at the 200 kA level. An advantage of the last two conductors is the provision for a direct bond between the rod and down conductor, minimizing resistance.

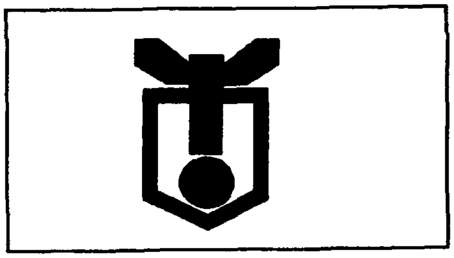

**Figure 11** AB-1373 connector (side view).

Other variables exist when considering system bonding. Area of the bond, pressure and materials in contact are significant factors. Since material properties are significant in bonding, consider the materials that contact each other in the system. Table 9 illustrates differences in junction resistances, given equal contact area and pressure. In general, malleable metals such as brass and copper provide better bonds at lesser pressure than steel. If a steel ground rod is used, consider providing direct bonding of the copper conductor to the rod or use of a copper lug.

Bond area is equally significant. The area of the bond should at least equal the cross-sectional area of the down conductor used. Since resistance is a function given by:

$$R=\frac{\rho l}{A}$$

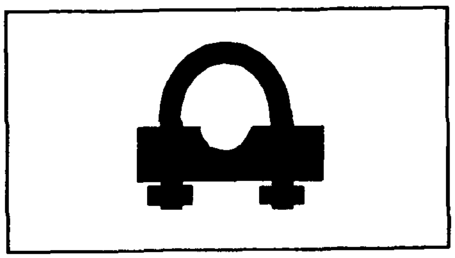

**Figure 12** U-bolt connector (side view).

Where: $\rho$= resistivity
R= resistance

l= path length
A= cross-sectional area

Noting the inverse proportionality of the area, we realize that maximizing area results in minimum resistance.

We also noted that bond pressure affects the resistance, and pointed out that bond pressure is inversely proportional to resistance. Tightening any of the above connectors with a hand tool should provide an adequate pressure. Resistance as a function of pressure is illustrated in figure 13. Note that the lowest resistances are achieved by junctions of the more malleable metals at lower pressures. A good design rule is that a bond should have less resistance than .6 meter of the down conductor. If the adequacy of the bond is in question, find the bond pressure and compare it to the data in figure 13. Since bond area is a linear term in the resistance relationship, by taking a simple ratio of the bond area given in figure 13 to your system's bond area, an approximate value of the junction resistance can be found. In general, use of one of the above connectors with tool-assisted tightening is adequate.

**Table 9** Comparative bonding material resistance.

| Bond Materials | Resistance ($\mu\Omega$) |
|---|---|
| Brass-Brass | 6 |
| Al-Al | 25 |
| Brass-Al | 50 |
| Brass-Steel | 150 |
| Al-Steel | 300 |
| Steel-Steel | 1500 |

(Given for 6.45 $cm^2$ bond area, 11.3 N-m fastener torque)

Achievement of an adequate bond is essential in structural components if they are used in the lightning protection system. In a tower or framework assembly, this is simple. The bolting or welding inherent to the structure should provide an adequate bond. In the case of a system using tubular segments, such as a mast, the bond is not readily achieved. Consider the load of the mast and the force it induces on the contact cross-section in the tubular segments. This force is essentially the sum of the weight of the antenna assembly and downward force

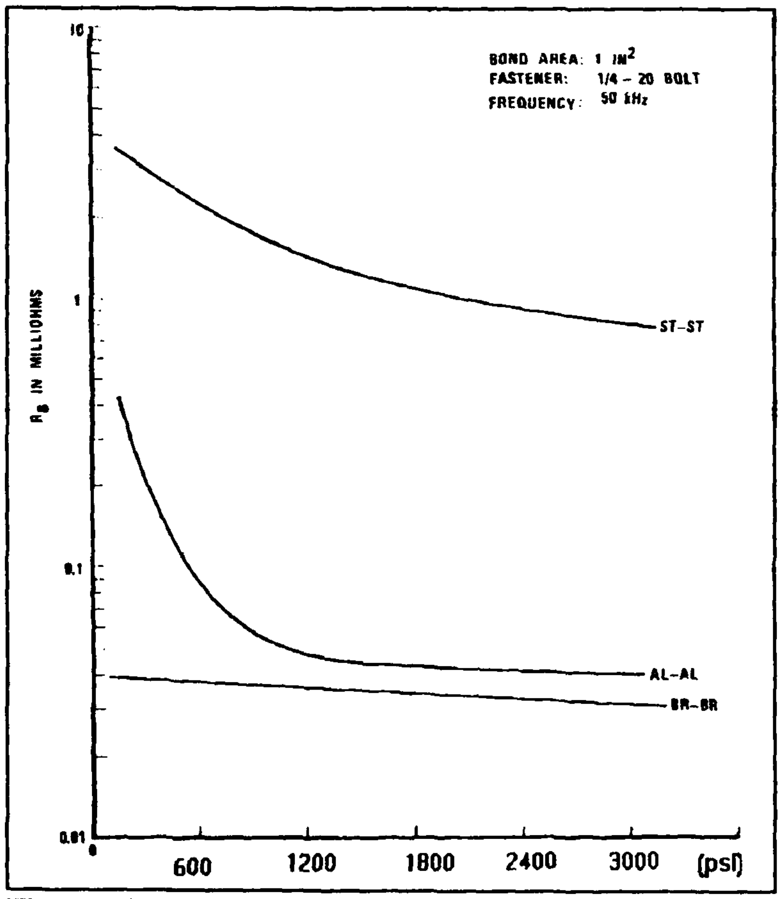


**Figure 13** Bond pressure vs. resistance.

exerted by tension in guy wires. We will examine this consideration in a later case study.

A system combining these connectors joining a simulated air terminal and ground rod to a #3 copper braid down conductor was repetitively tested at 205 kA with negligible degradation.

*Ground Rods*

The ground rod, sometimes referred to as the "earth termination," is the component which dissipates the lightning current. It is the single greatest resistive component in the lightning protection system. Minimization of the resistance to earth is critical to the effectiveness of the lightning protection system. As determined before, resistance minimization can reduce the chance of flashover and other undesirable effects. The resistance of various ground rod configurations can be calculated and considered in design. Let's consider different typical ground rod configurations for their resistance to earth. The resistance of a single ground rod of length, L, and radius, a, is:

$$R_{rod}=\frac{\rho}{2\pi L}(\ln\frac{4L}{a}-1)$$

For two ground rods separated by a distance, s, greater than their length:

$$R_{s>L}=\frac{\rho}{2\pi L}(\ln\frac{4L}{a}-1)+\frac{\rho}{4\pi s}(1-\frac{L^2}{3s^8}+\frac{2L^4}{5s^4})$$

For two ground rods separated by a distance less than their length:

$$R_{s<L}=\frac{\rho}{2\pi L}(\ln\frac{4L}{a}+\ln\frac{4L}{s}-2+\frac{s}{2L}-\frac{s^2}{16L^2}+\frac{s^4}{512L^4})$$

For a buried horizontal round plate of radius, a, and depth s/2:

$$R_{plate}=\frac{\rho}{8a}+\frac{\rho}{4\pi s}(1+\frac{7a^2}{12s^2}+\frac{33a^4}{40s^4}....)$$

where dimensions are in meters and resistivity in ohm-meters.[18]

Approximate typical soil resistivities are given in table 10; for more detail see MIL-HDBK-419A. Since the specific operating environment for a tactical system is not usually known, the approximate values are useful for estimating the earth resistance.

A particular hazard associated with ground rods is the nature of the rod to generate a potential gradient on the earth's surface when it is dissipating current. This hazard is known

[18] IEEE STD 142-1972, *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems*.

as the step potential. When the grounding system dissipates current it generates equipotential shells concentrically. If a person were in this potential gradient area, straddling two of the equipotential lines, current can travel across the body. This effect accounts for many of the injuries attributed to lightning. In general, locate the grounding system as far away as possible from areas which contain personnel. As was mentioned before, only personnel within a protected shelter or structure are afforded a reasonable level of protection from lightning strikes. We can calculate the most dangerous area near the ground rod. The method used is done by taking the expression for the potential on the earth surface from a single ground rod found in MIL-STD-419A:

**Table 10** Approximate soil resistivities.

| Soil Type | $\rho$, ohm-meters |
|---|---|
| wet organic | 10 |
| moist | $10^2$ |
| dry | $10^3$ |
| bed rock | $10^4$ |

Values from MIL-HDBK-419A, Table 2-2.

$$V(x) = \frac{.366\rho I_0}{l}\log\left(\frac{l}{x} + \sqrt{1+\frac{l^2}{x^2}}\right)$$

where l=rod length (m), $\rho$= soil resistivity (ohm-m), $I_0$= lightning current (amperes) and x= distance from the rod on the earths surface (m). We can plot the step potential from this relationship by calculating the potentials at .4 meter intervals (steps) for a standard 8-foot ground rod, with $\rho$=270 ohm-m subject to a 200 kA lightning strike in figure 14. The line that appears crossing near the bottom is the step voltage safety limit calculated from the expression given in MIL-HDBK-419A:

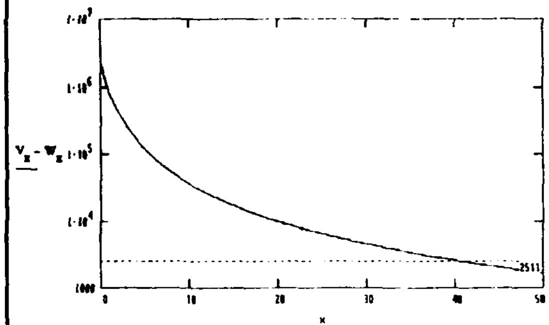

**Figure 14** Step potential vs. distance.

$$V_{step\ safe} = \frac{165+\rho}{\sqrt{t}}$$

where t is the shock duration from .03 to 3 seconds. In the figure the duration considered is the minimum, .03 second which is a few orders of magnitude longer than the A component of the lightning strike (and is therefore probably a few orders of magnitude on the conservative side). We can see from the plot that the minimum safe distance is about 41 meters! The so-called "safe distance" will not prevent personnel from receiving a shock, rather it is the minimum distance to prevent serious injury. Keep the grounding system as far as possible from personnel.

The design of the lightning protection system is essentially simple. Now that we examined

the components in high detail, we can fit this simple system using the design considerations given to applications. Usually, the lightning protection subsystem design considerations presented are not a factor until a specific obstacle arising from the requirements imposed on the overall design occurs. We can now examine real systems and apply the design considerations we've learned.

## Chapter 4 - Lightning Protection Applications

*Case Study - AB-621 antenna mast*

In the early 1980's testing of the AB-621 antenna mast found that no lightning protection measures were considered on this system. During the next two years, after discussion of various requirements, a lightning protection system was installed on this mast. The protection eventually installed provided an aluminum braided strap that connected a mounting lug on the base of the mast to a standard ground rod. An air terminal was not installed in the belief that it would interfere with the antenna. No down conductor was installed because that mast was aluminum and considered electrically continuous. Before this modification was completed, a lightning strike in the summer of 1982 caused severe damage to a communications shelter. Let's review the system and the design and installation of the lightning protection system.

The AB-621, illustrated in figure 15, is constructed of aluminum alloy and is a sectional, tubular mast. It is deployed by means of a "launcher" which lifts each section of the mast in turn, elevating the antenna assembly. The antenna is a dish with a waveguide leading into the communications equipment.

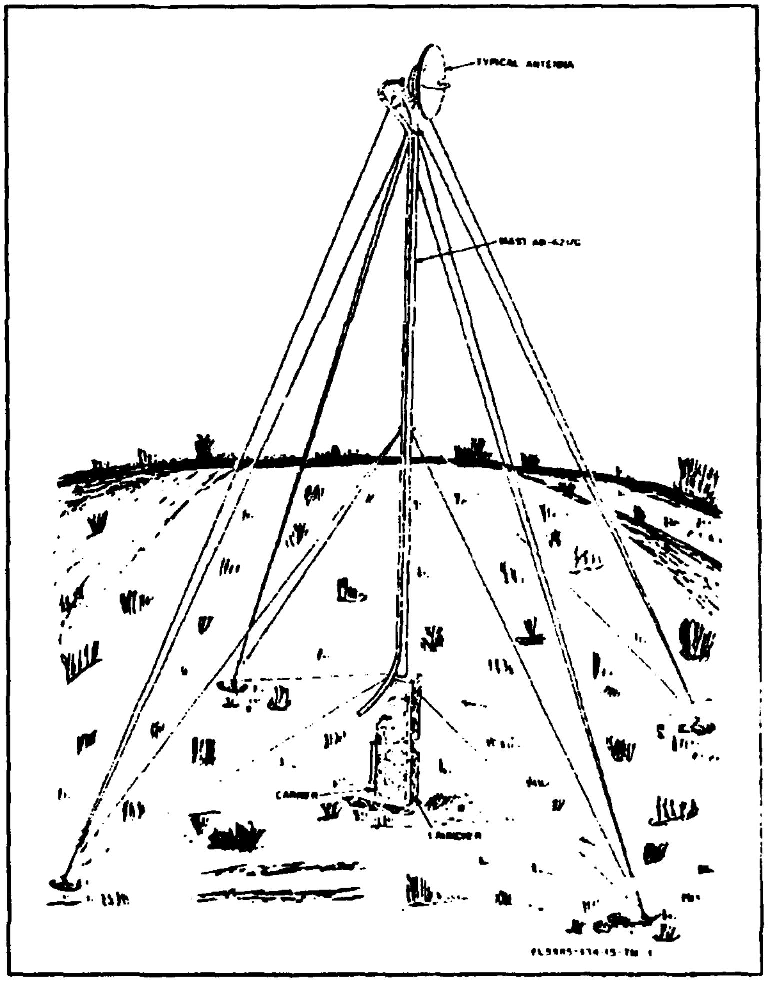

Figure 15 AB-621 antenna mast.

Let's begin with a risk assessment of this antenna. The height of the AB-621 is 30.5 meters. First, let's assign probability categories for this system. Supposing a fleet of 1000 masts and a 15 year life, we can construct table 11.
To clarify probability assignment we've made two columns under occurrences. For instance, the occasional category means that 7 systems will be damaged by lightning per year in the entire fleet or 100 systems over the entire 15-year life. Dividing the annual number by the number of systems yields a probability that one system will get hit by lightning. Performing the

calculation, we find that the probability is about .35%. Remember this assignment is arbitrary and depends on what you believe is a suitable category upon referring to table 3 in chapter 2.

**Table 11** Hypothetical probability assignment table for AB-621.

| FREQUENCY | OCCURRENCES | |
|---|---|---|
| CATEGORY | Annual/Fleet | FLEET LIFE |
| A/FREQUENT | $X_1 \geq 20$ | $X_1 \geq 300$ |
| B/PROBABLE | $X_1 \geq 13 \geq X_2$ | $X_1 \geq 200 \geq X_2$ |
| C/OCCASIONAL | $X_2 \geq 7 \geq X_3$ | $X_2 \geq 100 \geq X_3$ |
| D/REMOTE | $X_3 \geq 3.5 \geq X_4$ | $X_3 \geq 50 \geq X_4$ |
| E/IMPROBABLE | $X_4 \geq .6$ | $X_4 \geq 10$ |

Next, let's calculate the probability of lightning strike to this system. Since this is a tactical system subject to worldwide operation, we will estimate many of the variables in accordance with the recommendations in chapter 2. We estimate the number of thunderstorm days per year, $D_T=60$, and the fraction of cloud to ground flashes as $p=.33$. Recalling the relation for flash density from page 10:

$$p=0.1(1+(\frac{l}{30})^2)$$

we calculate $F_D=8.3$. Next, we can find the lightning attractive area, A. Using method 1, and a 10 meter effective height yields $A=.01\ km^2$. Assuming the system is used frequently let's set N, the fractional operating year, to .8, corresponding to 292 days of use per year. Finding $H_{UY}$, the number of strikes per operating year, is then straightforward. Recall:

$$H_{uy}=AF_DN$$

The calculation yields $H_{UY}=.066$, which corresponds to a 6.6% chance that one system will receive a lightning strike in one year. Multiply our result by the number of units in the fleet to arrive at the number of systems we expect to receive lightning strikes in one year: $n=.066(1000)=66$ systems per year! (Consider a material failure coefficient of $C=1$, corresponding to no lightning protection.) Which probability category does this fall into? Examining table 11, the probability assignment is clearly "frequent." We are reasonably sure that this system needs lightning protection. If protection at the 2% level is installed, the material failure coefficient becomes .02, and then the number of systems per year damaged becomes $66(.02)=1.32$, which is a "remote" probability category.

To go further in risk assessment, we need to construct a damage severity table. Since this is a tactical system, readiness is a primary concern. The table we construct can reflect this. If our protection system, on an average, can limit damage to marginal, the risk according to the risk assessment table in figure 4 is III-D, marginal/remote, corresponding to a low risk and therefore an acceptable level of protection. We will examine the construction of the lightning protection system to determine whether this was achieved.

Reviewing the design, we find only grounding at the base of the mast with an aluminum strap. The ground rod is adequate as are the connections between the mast and the ground rod. It is a standard ground rod as was tested in the CECOM Safety Office test program, while the connectors are wingnut and lug assemblies. Following the design guidelines on pages 22-24, we recommend that they consist of brass or copper and that they are tightened with a hand tool. The down conductor is the aluminum mast barrel. Since the specifications call for reasonably heavy aluminum tubes and the contact area between sections is at least 10 $cm^2$, this material appears suitable. Examining the electrical continuity of the mast, we find a potential problem. Documentation on this system calculated the maximum contact pressure between the sections as 26 psi, about .18 MPa. Referring to figure 13, bond pressure vs. resistance, we find that the joint resistance at this low pressure is high for aluminum bonding. Supposing 1 milliohm per bond, this is greater than 2 feet of the conductor tube. If there are 12 sections, this becomes 12 milliohms, still quite less than the ground resistance of approximately 25-50 ohms. We can therefore accept this condition because the additional resistance is orders of magnitude smaller than the resistance to ground.

**Table 12** Damage severity table.

| Damage level | Time to repair |
|---|---|
| Catastrophic-I | impossible |
| Critical-II | $t > 10$ days, $t < 30$ days |
| Marginal-III | $t > 1$ days $t < 10$ days |
| Negligible-IV | $t < 1$ day |

Next let's examine the top of the system. No air terminal is provided in the design. The antenna is used as the air terminal. This is an assumed risk because it was thought that an air terminal would interfere with the antenna. Upon close examination, we conclude that this is probably not true. A dish antenna is directional. Installation of an air terminal behind the dish would probably not interfere with the main power lobe in the radiation pattern of the antenna. Secondly, closely examining the antenna, we find that the waveguide leads directly out of the dish. It is not bonded to ground at this point. This provides a low impedance path to the communications equipment. Reevaluating this system, we now doubt that the lightning protection would divert the current from the equipment. The risk then becomes correspondingly high. As events proved before installation of the grounding system, the waveguide provided a better path to ground than the mast did. In 1982, a lightning strike to an AB-621 caused critical damage to a communications shelter. Reexamining the design using the guidelines in chapter 4, we would install an air terminal and bond it to the mast providing an electrically continuous path to divert the lightning current from the antenna and waveguide. We would then install the grounding system but replace the aluminum strap with #3 copper braid and independently ground the waveguide. Perhaps we would consider an insulating coating for the waveguide at the top of the mast to reduce the likelihood of flashover. We are relatively sure that a few additional precautions in system design would have reduced the severity of the accident.

*Case Study - AB-1373 antenna mast*

This mast, diagramed in figure 16, provides a good design for lightning protection. It has an air terminal, down conductor, and two ground rods. The brass connectors are robust and suitable for the application. Since the mast itself is a carbon-fiber composite, it provides a high impedance path to ground. The tip of the air terminal is stainless steel, and is separated from the antenna assembly by fiberglass extensions which provide better flashover clearance. A coaxial signal cable with surge protection at the equipment end is used in this antenna system, reducing the probability of flashover. The cone of protection provided is approximately 38 degrees, which is suitable for this application. It is a good lightning protection system design. Also, we will consider the AB-1373 as part of the OE-481 system which consists of 2-3 antenna masts and a support pallet. Upon reviewing the technical specifications for this system, two problems became evident.

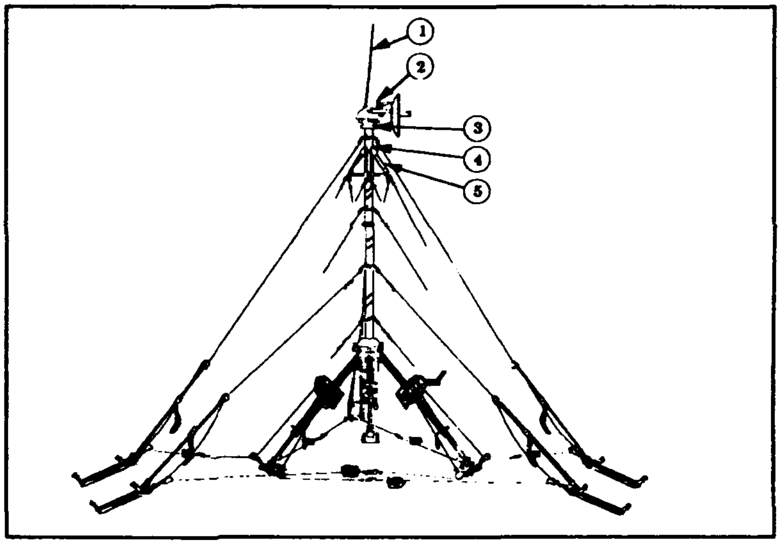


**Figure 16** AB-1373 antenna mast.

A procedural problem was detected in the technical manual. It is reproduced in figure 17. The instructions called for coiling the excess down conductor about the fiberglass extensions. This creates an inductor and increases the chance of flashover. Using the relation for the inductance of a cylindrical helix coil:

$$\frac{L}{I}=\mu N^2 A_{coil}$$

where N=number of turns, A=coil cross-section, $\mu$=magnetic permeability. Performing this calculation supposing N=10, A=.008 m$^2$ (corresponding to a 5 cm radius) yields L/I=1X10$^{-6}$ H.

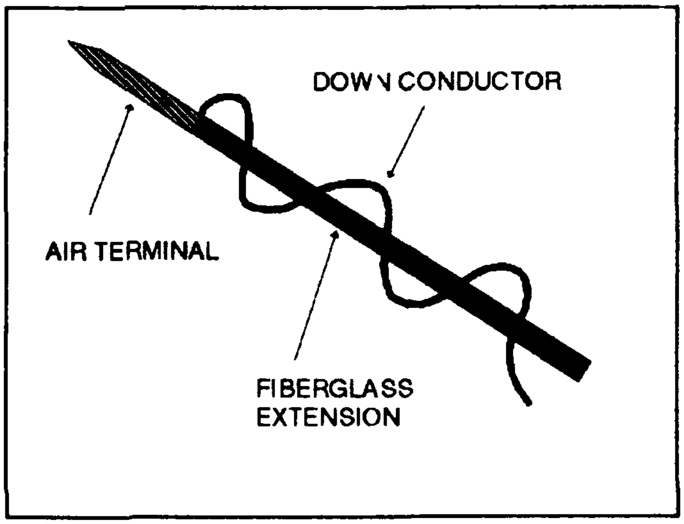


**Figure 17** Erroneous down conductor installation.

Using the previous relation v=LdI/dt for a typical lightning strike, we find v=12,500 volts. Using the relation for breakdown distance, we find D=.055 meter. We find that this

flashover increase of a few inches would not be significant. However this installation practice violates the principle that the conductor must be as straight as possible. A severe lightning strike to this would easily break the conductor. This oversight was corrected.

The next issue that developed was the questionable adequacy of the down conductor. It did not meet the class I requirements, and was thought unsuitable. Since compliance with industry standards would have precluded compliance with the system deployability/mobility requirements, we performed a risk assessment of the item.

As in the preceding case study, we constructed the probability table (table 13) and calculated the probability of strike to the mast.

**Table 13** Probability assignment table for AB-1373.

| FREQUENCY | OCCURRENCES | |
|---|---|---|
| CATEGORY | ANNUAL/FLEET | FLEET LIFE |
| A/FREQUENT | $40 \geq n$ | $400 \geq n$ |
| B/PROBABLE | $40 \geq n \geq 20$ | $400 \geq n \geq 200$ |
| C/OCCASIONAL | $20 \geq n \geq 2$ | $200 \geq n \geq 20$ |
| D/REMOTE | $2 \geq n \geq .5$ | $20 \geq n \geq 5$ |
| E/IMPROBABLE | $.5 \geq n$ | $5 \geq n$ |

Using average operating cases, $D_T=40$ and $p=.33$, results in:

$F_D= .007(40)^2(.33)= 4.3$ strikes to ground/year-km$^2$;

$H= AF_DN = .099$km$^2$(4.3 strikes to system/year-km$^2$)(.67) = .29 strikes to one system per year; where: A= lightning attractive area, N= operating year.

Since the masts operate in groups of three or two in close proximity, only one attractive area is considered.

To determine the total strikes to the whole fleet of OE-481, we use:

Total strikes= HLI = (.29 strikes to system/operating year)(10 operating years)(321 systems) =930 strikes expected in the operating life of the whole fleet of OE-481/TRC, where: L=system lifetime (assume 10 years); I=number in inventory (321 systems, 834 masts expected)

Then we consider the number that may experience damage from lightning due to failure of the ground conductor under load. From table 8, down conductor material statistics, assign a 15% failure category to the ground conductor. Factoring in the material failure coefficient C=.15 yields: 140 OE-481/TRC that experience damaging lightning strikes in the system lifetime. This falls into the occasional probability category. The most likely damage that a lightning strike would cause was determined to be damage to the antenna assembly, which could be corrected within one day or the entire system could work around one inactive mast. Using a damage assignment table similar to the one used in the previous case study, the risk was determined to be IV-C, negligible severity, occasional probability. Using the risk

assessment table in figure 4 indicates a low risk hazard. The down conductor was not replaced.

The accuracy of this prediction did not wait long for validation. In July of 1992, during user test of this system at Fort Gordon, Georgia, lightning struck an AB-1373 mast. While two personnel outside (remember, we recommend a permanent structure or grounded shelter for personnel protection) received a shock sensation, only the down conductor of this system was damaged. This damage did not affect system operation and was repaired.

## Chapter 5 - Synopsis

The intent of this technical report is to provide tested solutions to lightning protection problems often found in tactical communications systems. We have reviewed a brief history of lightning protection in these systems, learned how to assess risk of lightning damage, examined how to design to incorporate lightning protection and reviewed the design principles by studying real systems. Using the principles learned, we can apply realistic lightning protection to save cost and enhance reliability of tactical communications systems.

Remember that the solutions presented do not replace industry standards. The design guidelines provide alternative solutions when the industrial standards/codes are impractical for application. We have pointed out that in some cases, by deviating from the industrial standards and codes, a certain level of risk is assumed. (This is manifested in the assignment of the material failure coefficient.) Provided that the risk is low, or equal with the level of protection afforded by the standards and codes, the design principles in this report remain valid.

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